Project ID: mat245

LMCP P1B - Form-and-Print - AM for Localized Property Enhancement of High-strength Al Sheet

Alex Plotkowski (PI), Gerry Knapp, Tom Feldhausen, Ying Yang, Jamie Stump, Donovan Leonard, Amit Shyam

Oak Ridge National Laboratory

2022 DOE Vehicle Technologies Office Annual Merit Review
June 23, 2022

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

LMCP Thrust 1 Overview

Selective Processing of Aluminum Sheet

Timeline/Budget

- Lab Call Award: September 2020
- Kickoff: November 2020
- Project end: September 2023
- Percent complete: 50%

Barriers and Technical Targets

- **Materials Performance and Cost** limit the penetration of lightweight Al and Mg alloys into the entire range of vehicles
- **Recyclability** is complex due to large number of different alloys
- **Throughput and cost** of additive manufacturing processes
- **Crack-free processing** of high-performance Al sheet

Thrust 1. Selective Processing of Aluminum Sheet		
Project	**Title**	**FY22**
1A	Sheet Materials with Local Property Variation (PNNL/ANL)	$500k
1B	Form-and-Print: AM for Localized Property Enhancement (ORNL)	$200k
1C1	High-Shear Thermomechanical Processing (PNNL)	$400k
1C2	Localized Thermal-Mechanical Processing (ORNL)	$200k
	Thrust Total	$1,300k

Partners

- Project 1B Lead
  - Oak Ridge National Laboratory
- Industry Engagement
  - Ford Motor Company
  - CompuTherm
  - Mazak
  - Lincoln Electric
- Thrust 4
  - Computation
  - APT (PNNL)

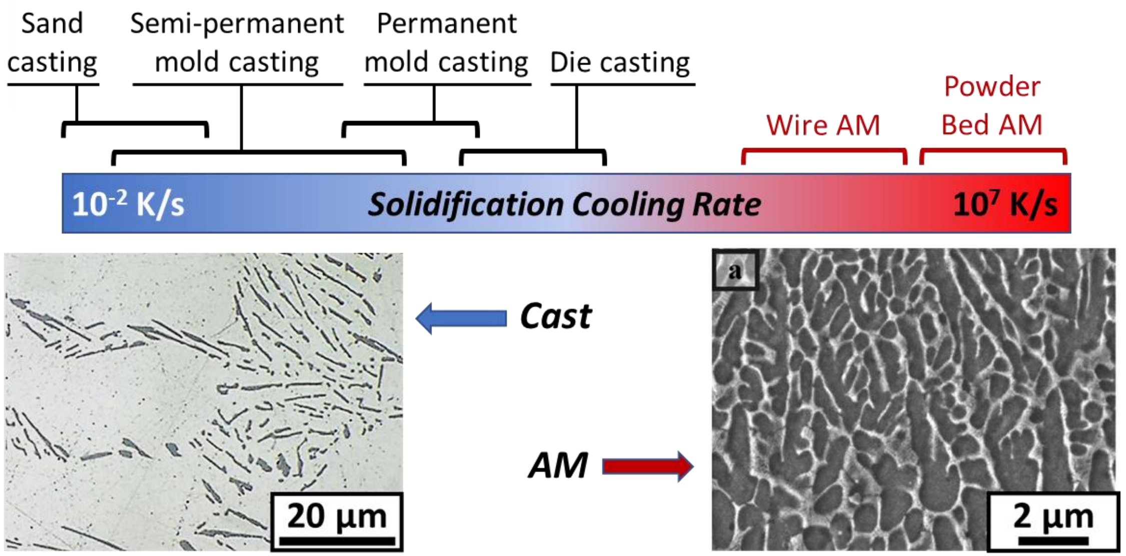
Relevance

Challenges and Opportunities

- Enable cost effective utilization of additive manufacturing (AM) for light-weighting automotive components
- Improve recycling practices

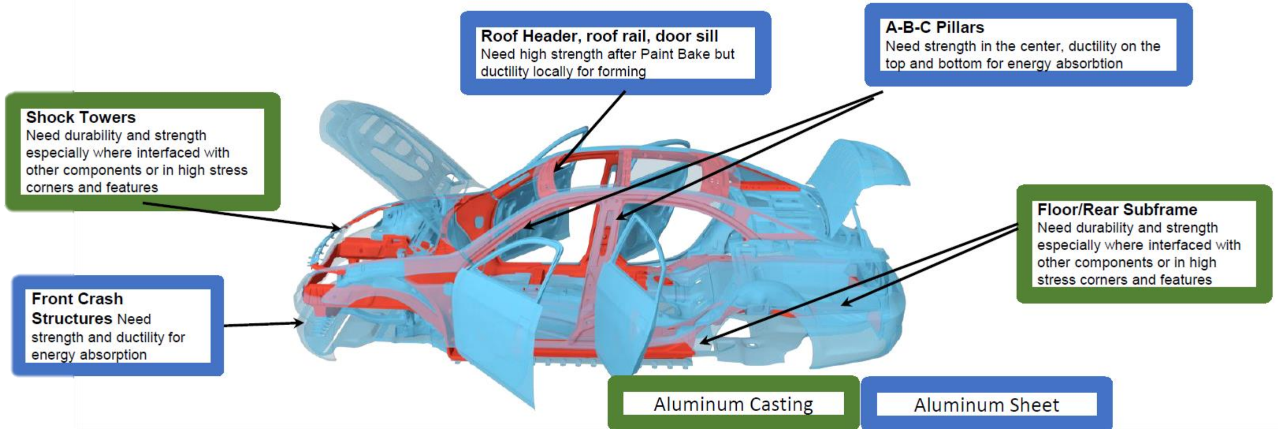
Objective

- Obtain complementary material properties and match to automotive applications
- Manufacture complex geometries while minimizing cycle time and cost



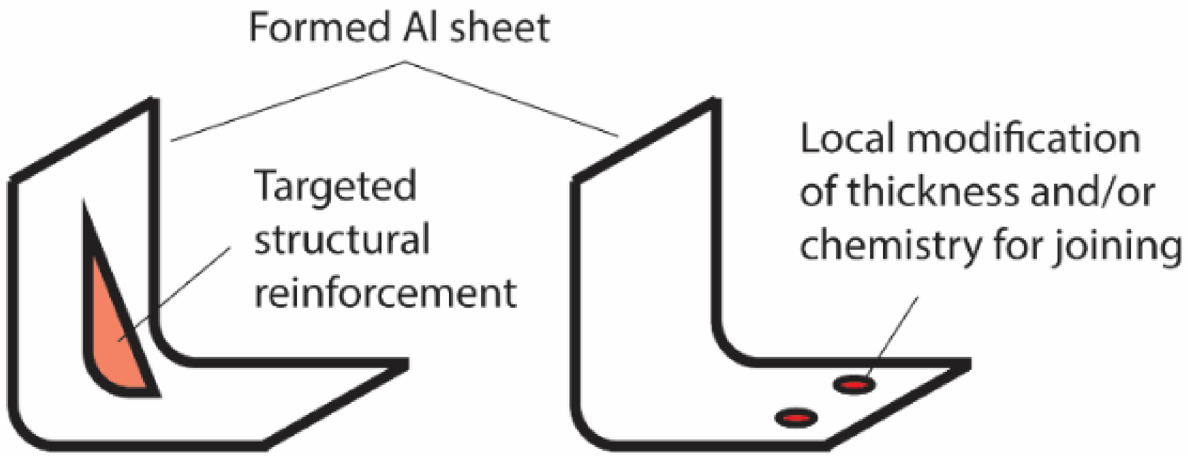
Impact

- Lighter weight, higher performance aluminum sheet products through selective application of AM
- Part count reduction



Approach: AM to Modify Local Properties and Structure

- AM to modify microstructure and geometry of formed Aluminum sheet
  - Enable advanced structural designs for lightweighting
  - Local microstructure modification for improved properties
  - Local chemistry modification to enable subsequent operations (e.g., joining)
- Focus on **6xxx** Al sheet
- Minimize application of AM to **most impactful and valuable** features



Approach: Process Selection

Laser powder
bed fusion

Blown powder
DED

Hybrid powder DED
+ machining

Mazak VC-500X Hybrid
Manufacturing System

Wire feed
- Cost effective feedstock
- High deposition rates

Laser hot-wire
- Detailed control over energy input
- Deposition on thin substrates
- Control of microstructure

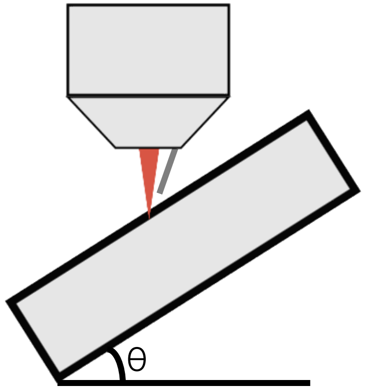
Machining capabilities
- Prepping and finishing operations

Large build volume
- Suitable for automotive components

Manufactured in USA

Accomplishments: Initial Deposits of Al 4043 on 6061

- Single bead deposits were performed on 6061-T6 substrate to determine appropriate process parameters
- Surface finish was found to be critical, rougher surface resulted in better weld beads



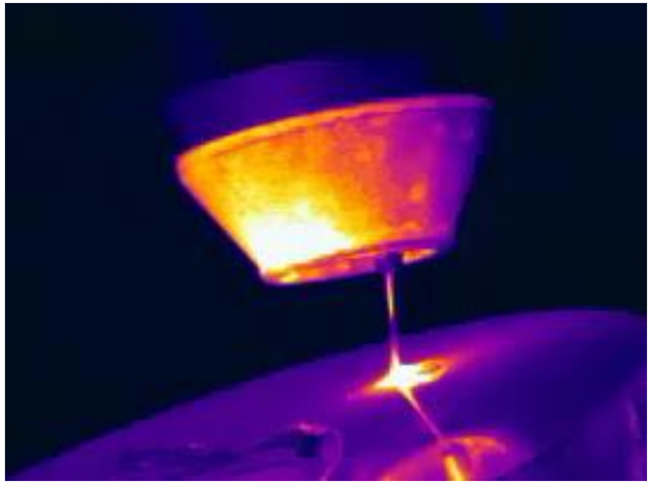
Substrate was tilted at angle to laser to prevent back-reflection

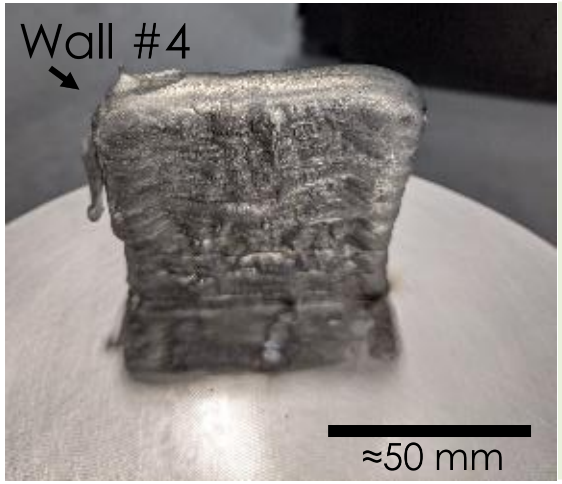
Table 1. Initial parameter set

Parameter	Value
Laser Power	4000 W
Wire Power	104 W
Wire feed rate	88 in/min
Traverse rate	406 mm/min
Gas flow	20 L/min (Argon)
Initial dwell*	5 s with gas only 2 s gas + laser
End dwell*	0.1 s gas + laser

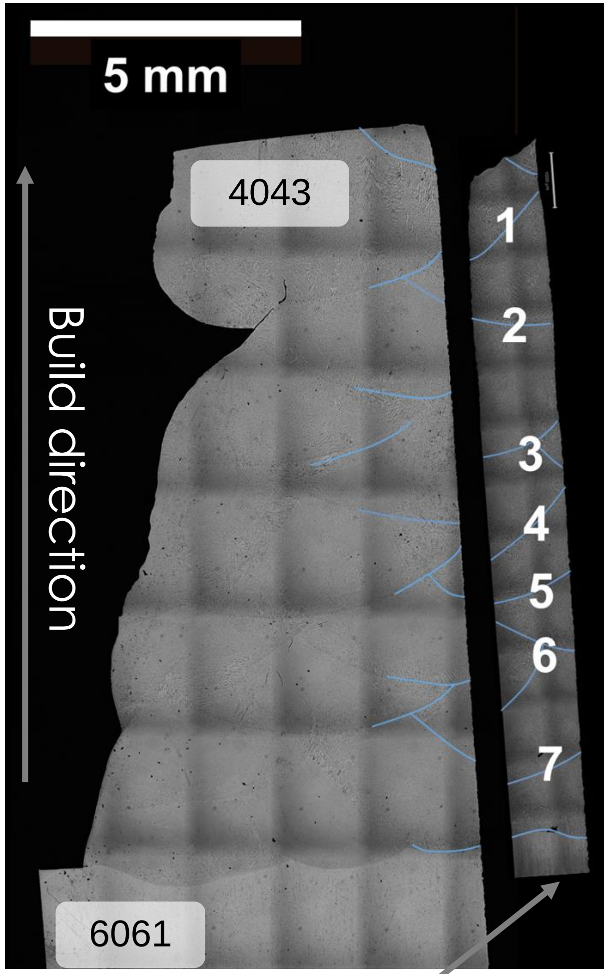
Single bead deposits of Al 4043 wire on Al 6061 substrate

Accomplishments: Printing Simple Geometries – Microstructure Variation as a Function of Build Height

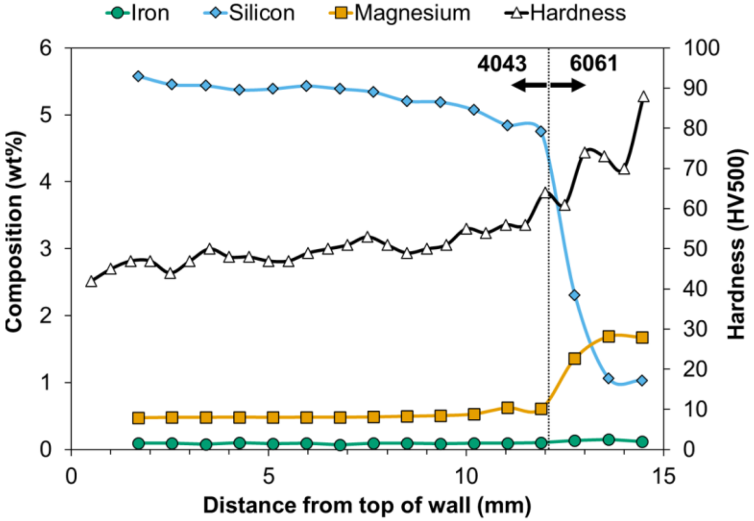




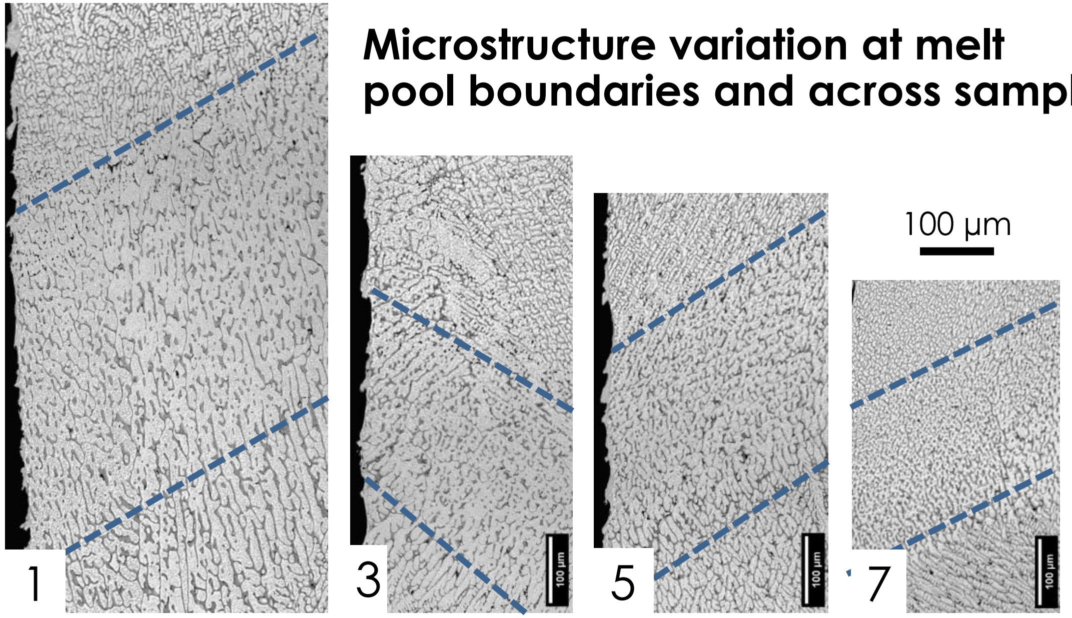
Using the Al 4043 wire on the 6061 substrate, an approximately 50 mm tall wall was built using the parameters in Table 1.



Tensile bar gage section



Microstructure variation at melt pool boundaries and across sample

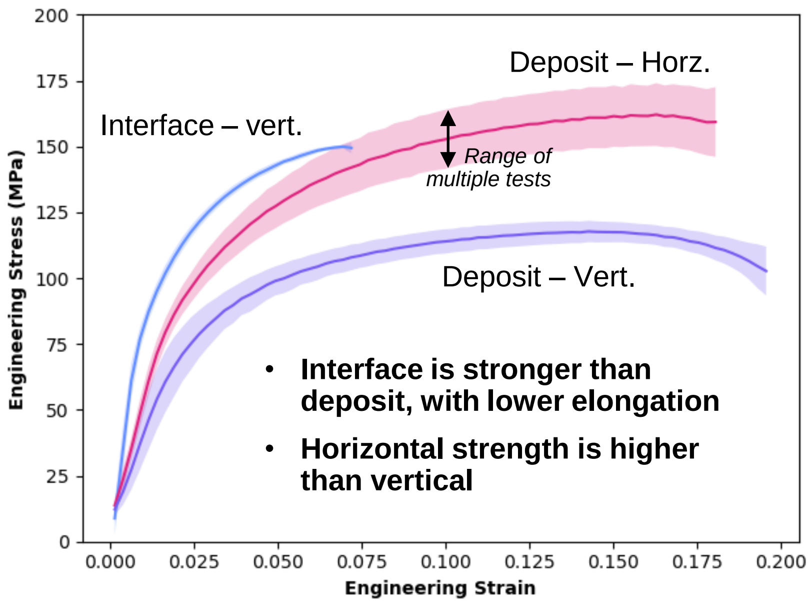


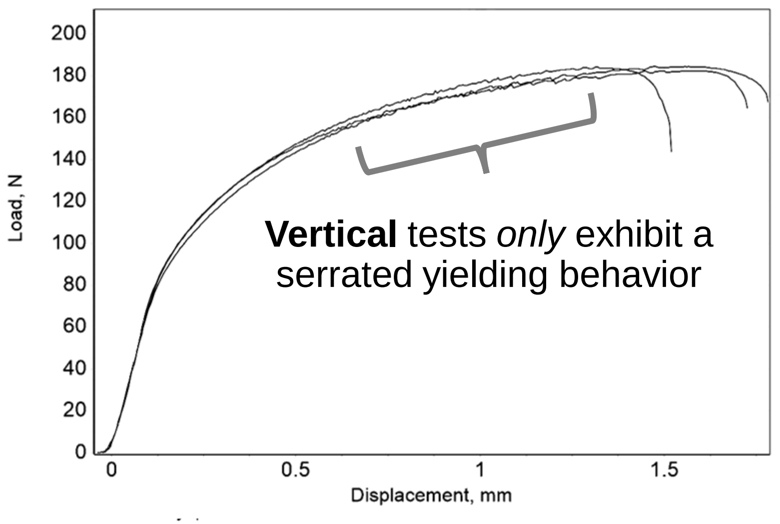
Top

Interface

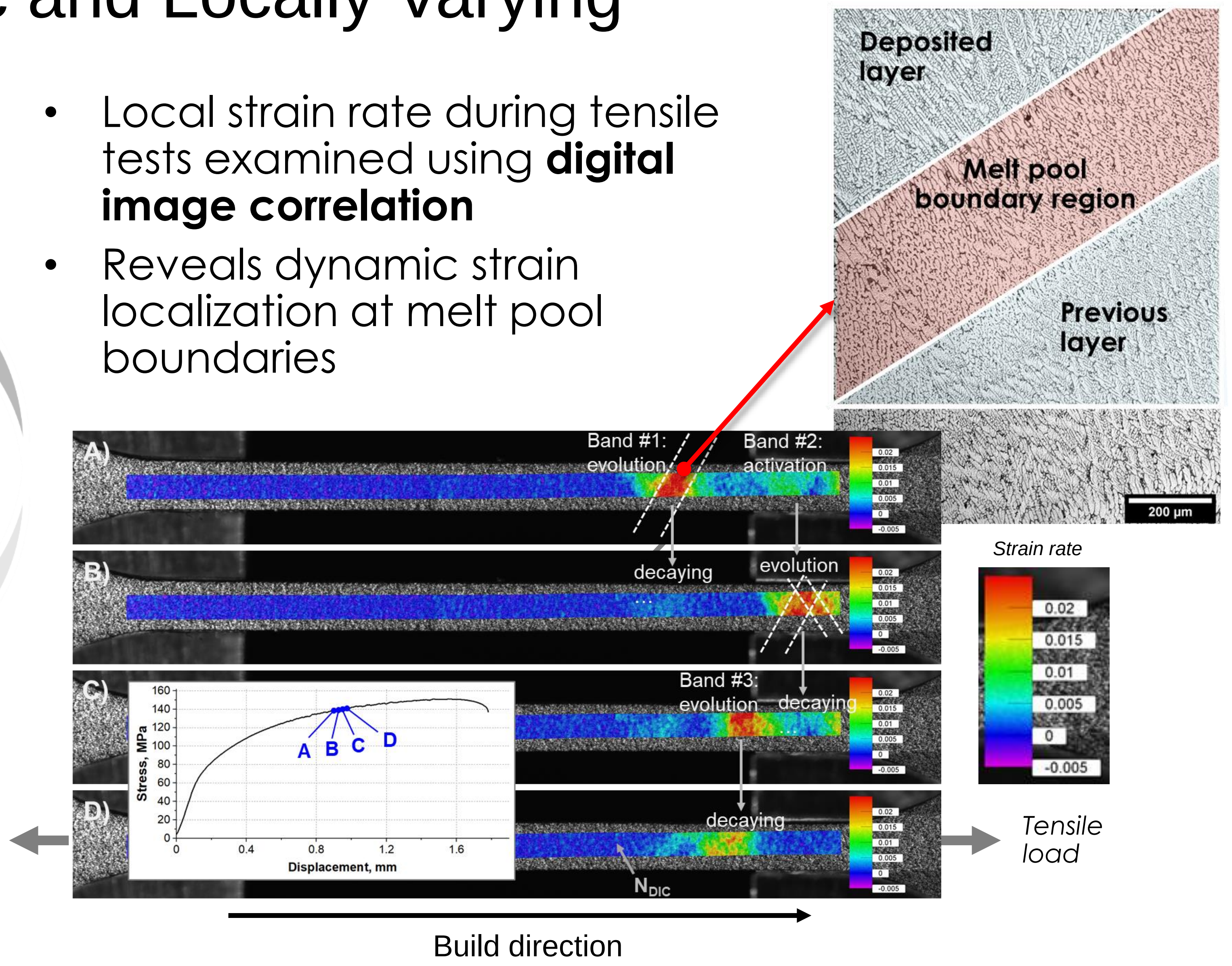
OAK RIDGE National Laboratory | MANUFACTURING DEMONSTRATION FACILITY

Accomplishments: Mechanical Properties of 4043/6061 Samples are Anisotropic and Locally Varying





- Local strain rate during tensile tests examined using **digital image correlation**
- Reveals dynamic strain localization at melt pool boundaries

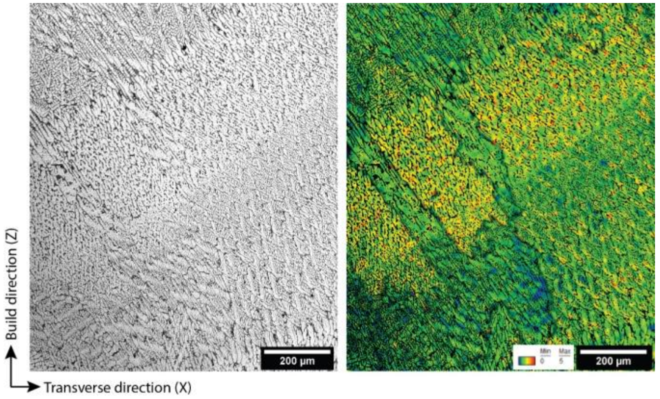


Accomplishments: Heterogeneous Deformation driven by Local Variation in Strain Hardening Behavior

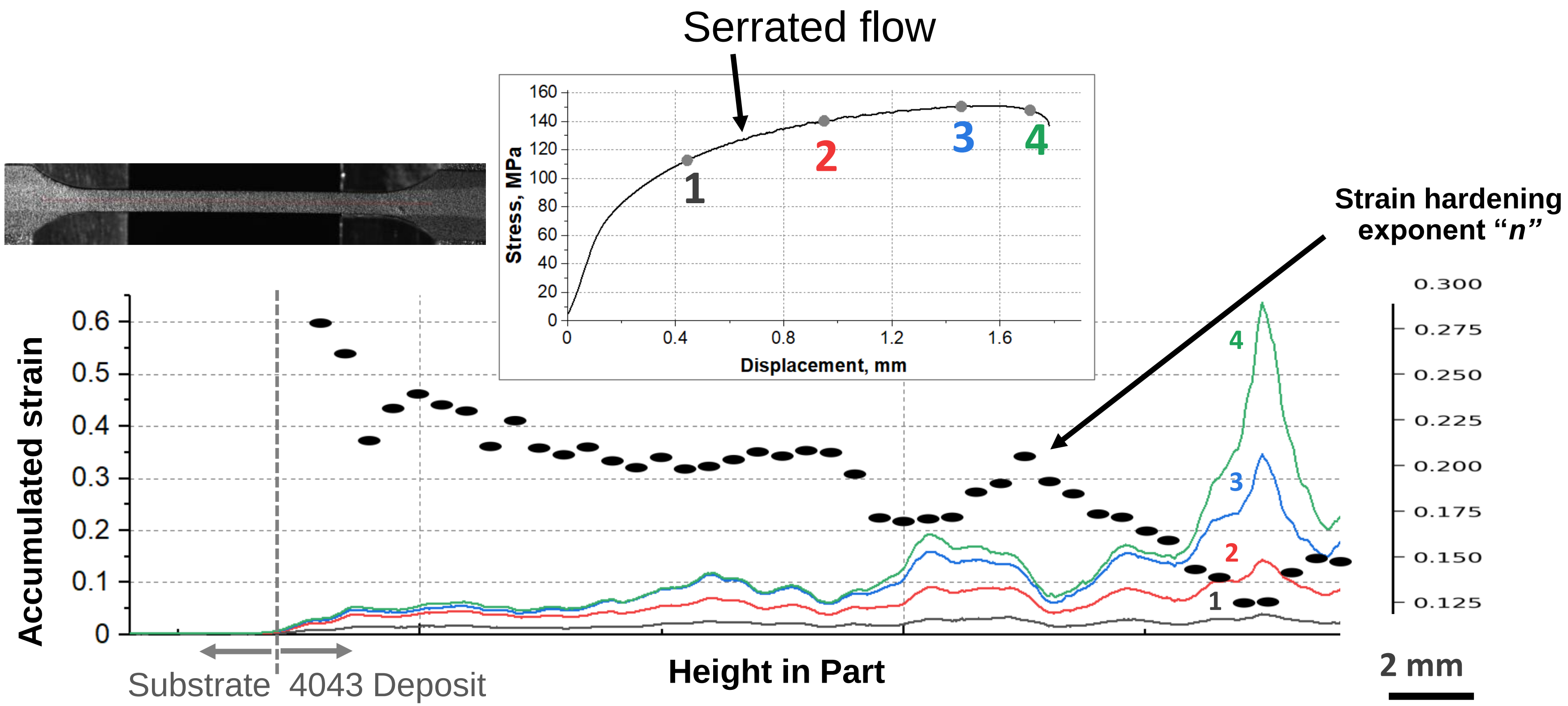
- Extracted local stress-strain curves from DIC data and extracted strain hardening behavior

$$\sigma = K\varepsilon^{n}$$

- Area of high strain accumulation are correlated with low strain hardening exponent

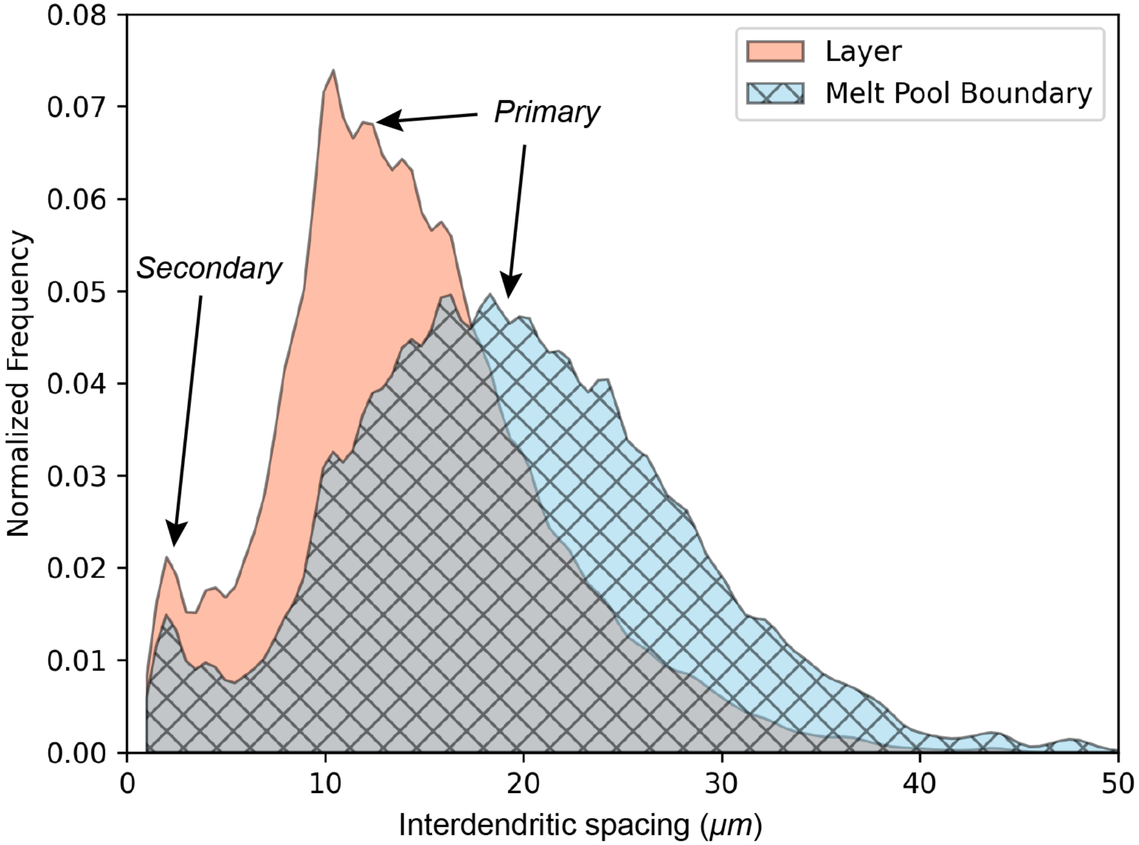


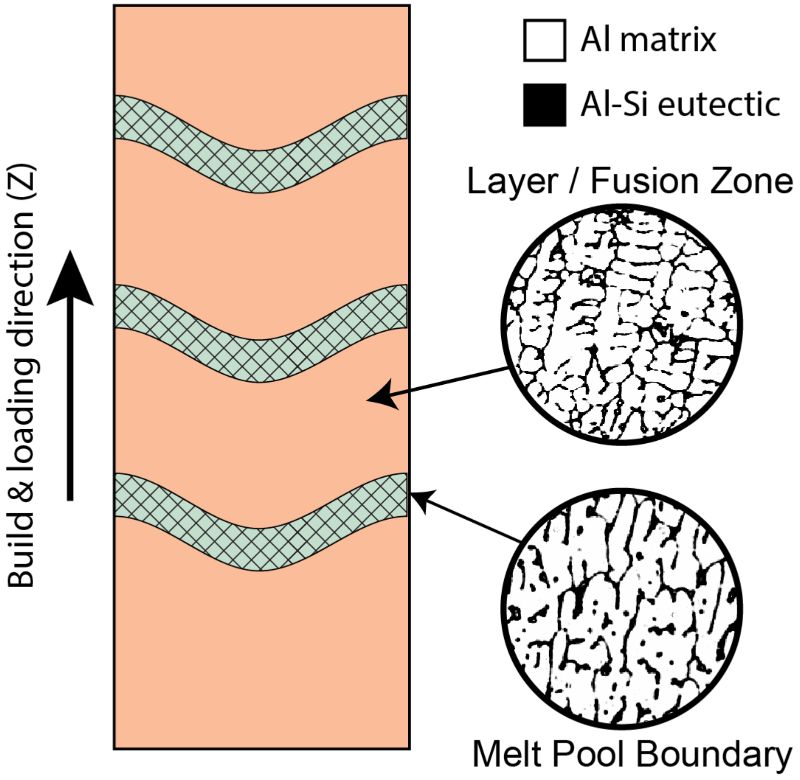
Localized deformation in melt pool boundary (right: kernel average misorientation)



Accomplishments: Microstructure-Property Correlations

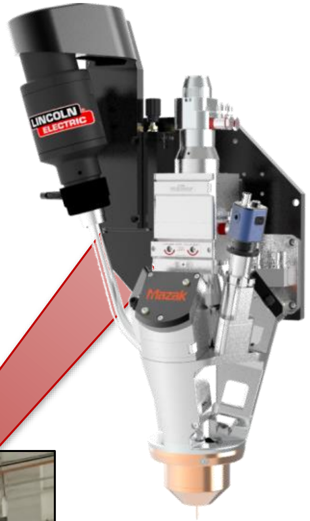
- Spatial variation in strain hardening rate is dependent upon local microstructural length scale
- Coarser microstructure at melt pool boundaries is caused by partial remelting during deposition of the subsequent layer



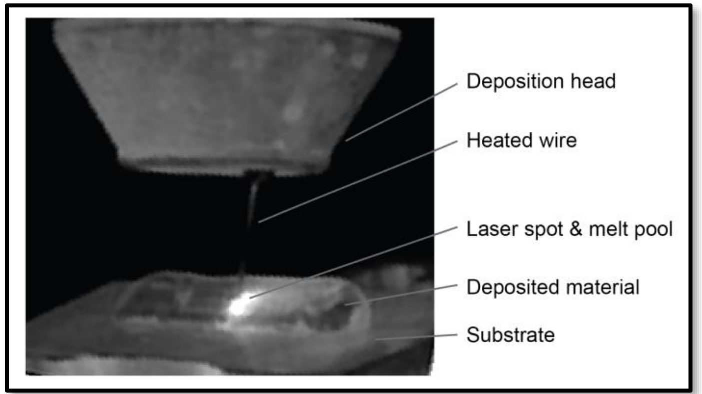


Accomplishments: Installation of Mazak Hybrid Manufacturing System at ORNL

- Large-scale hybrid **laser hot-wire system** in collaboration with **Mazak**
- Large build volume
  - 0.5m diameter
  - 1.5m height
- High-speed 5-axis machining capabilities

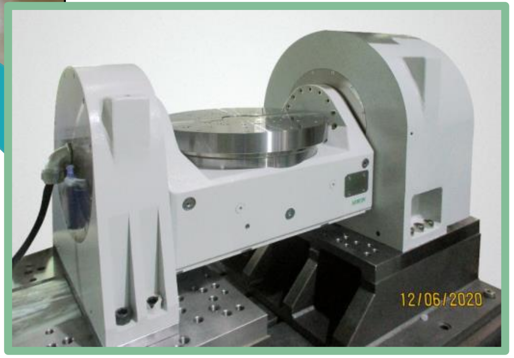


LE Tri-beam Deposition Head



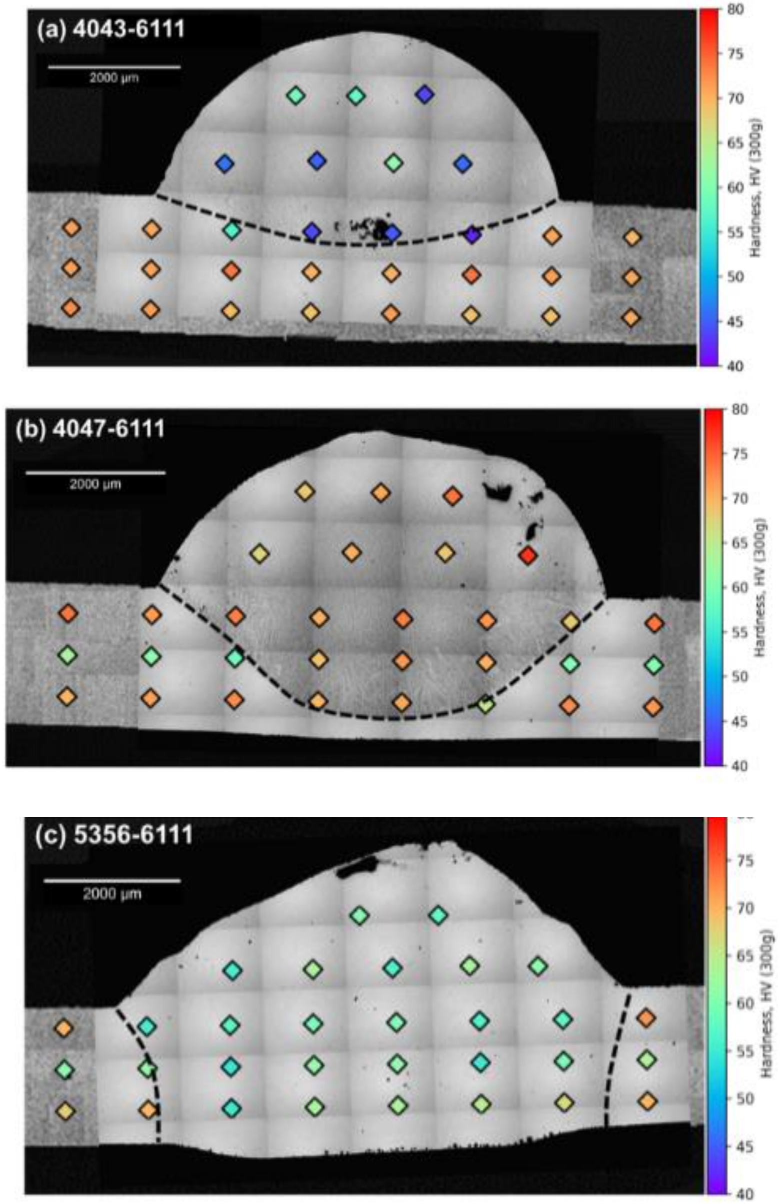
Melt pool monitoring system

5-Axis Table



Accomplishments: Varying Local Properties by Depositing Different Alloys

- Deposition of different filler wires on 6111 wrought substrate
  - 4043, 4047, 5356
- Identifying appropriate process conditions
- Initial comparison of properties
- Seeking range of complementary properties to be matched to applications



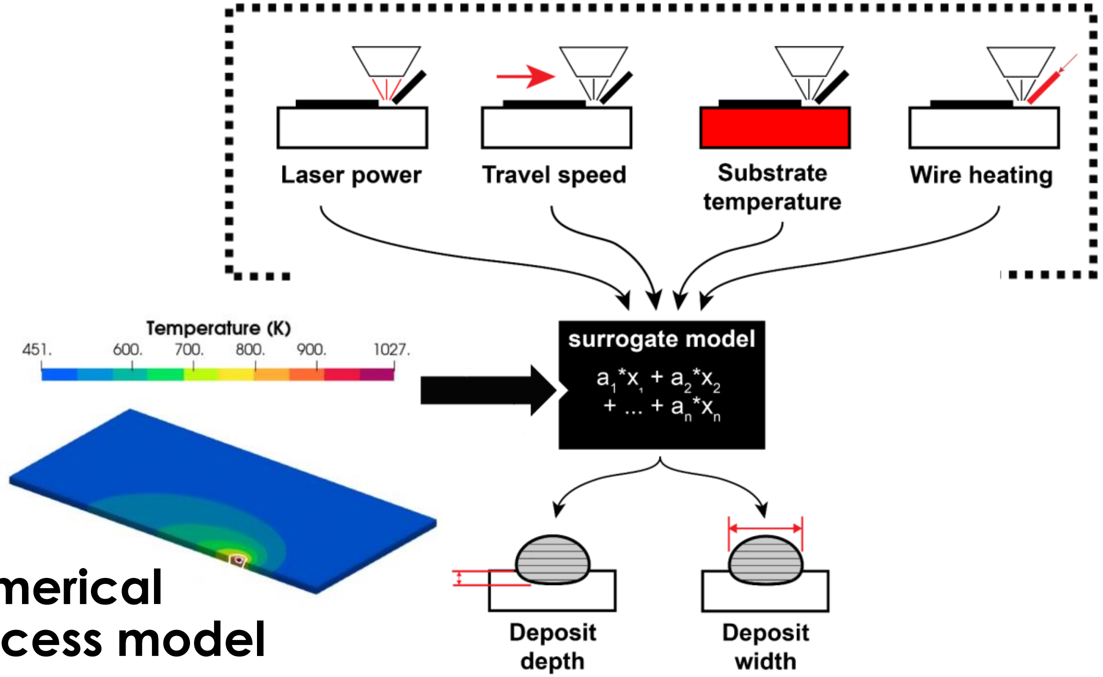
Al 4043
- Hypoeutectic Al-Si
- Highly weldable
- Good ductility

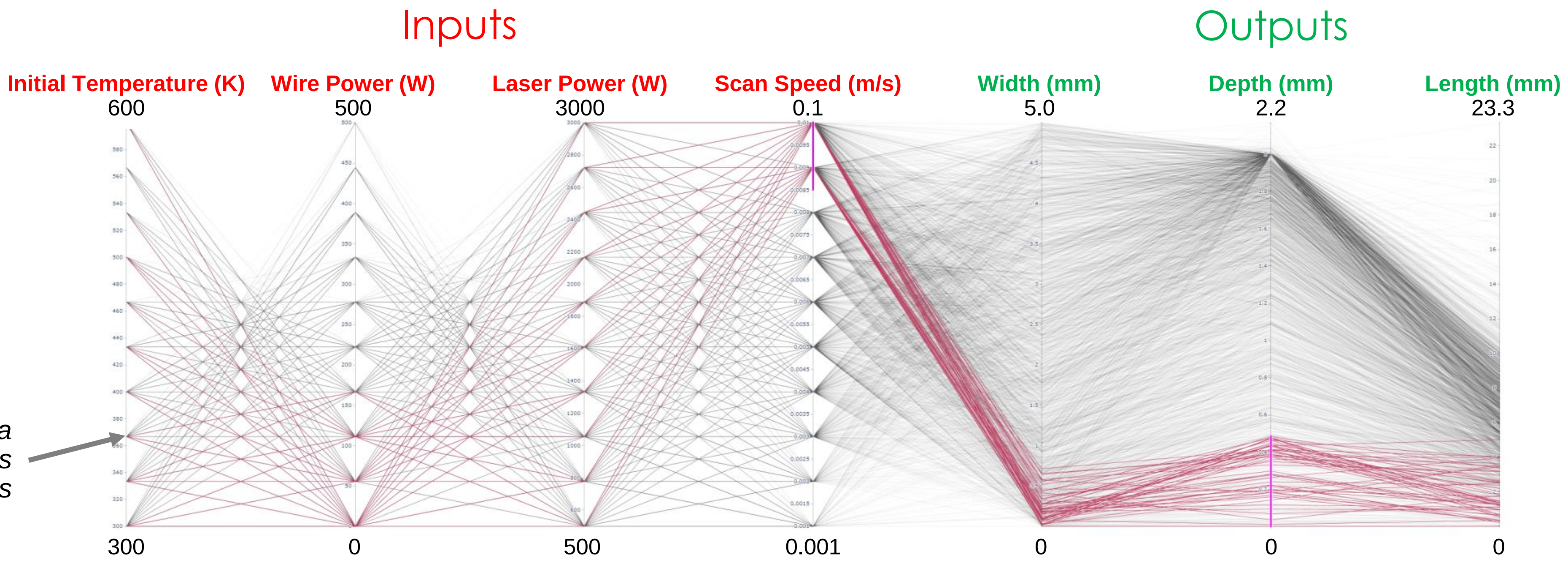
Al 4047
- Near-eutectic Al-Si
- Highly weldable
- Higher strength

Al 5356
- Al-Mg, low Si
- Less weldable
- Higher strength
- Good toughness

Accomplishments: Computational Tools for Generating and Analyzing Large Data Sets

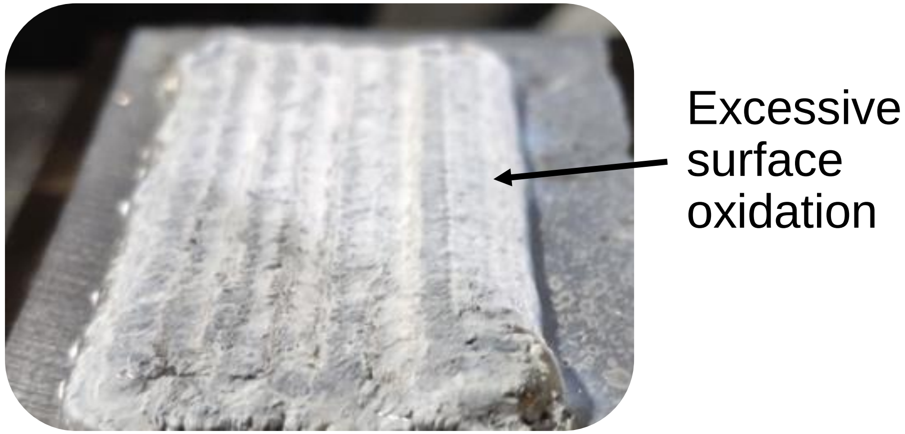
- Numerical process model developed to predict heat transfer and solidification in laser hot wire processing of thin sheets
- Used numerical model to develop a fast-acting surrogate
- Sample the surrogate to create large data sets, which may be visualized using parallel coordinate plots

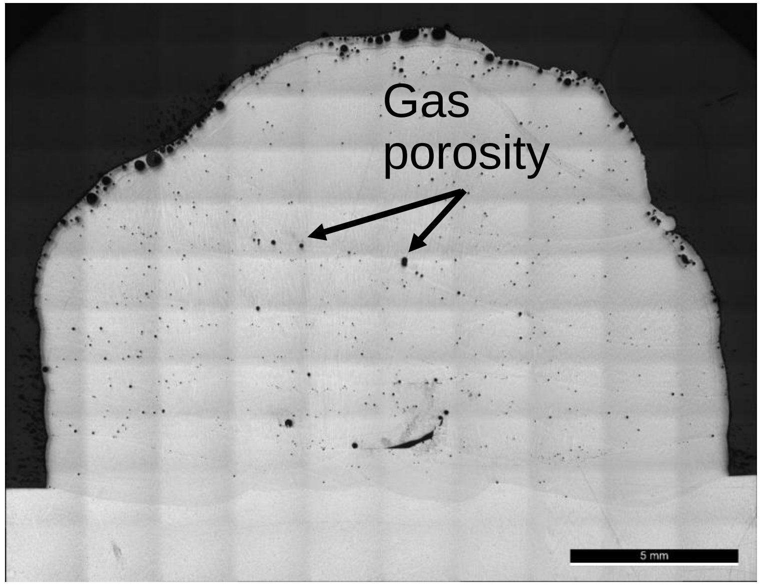




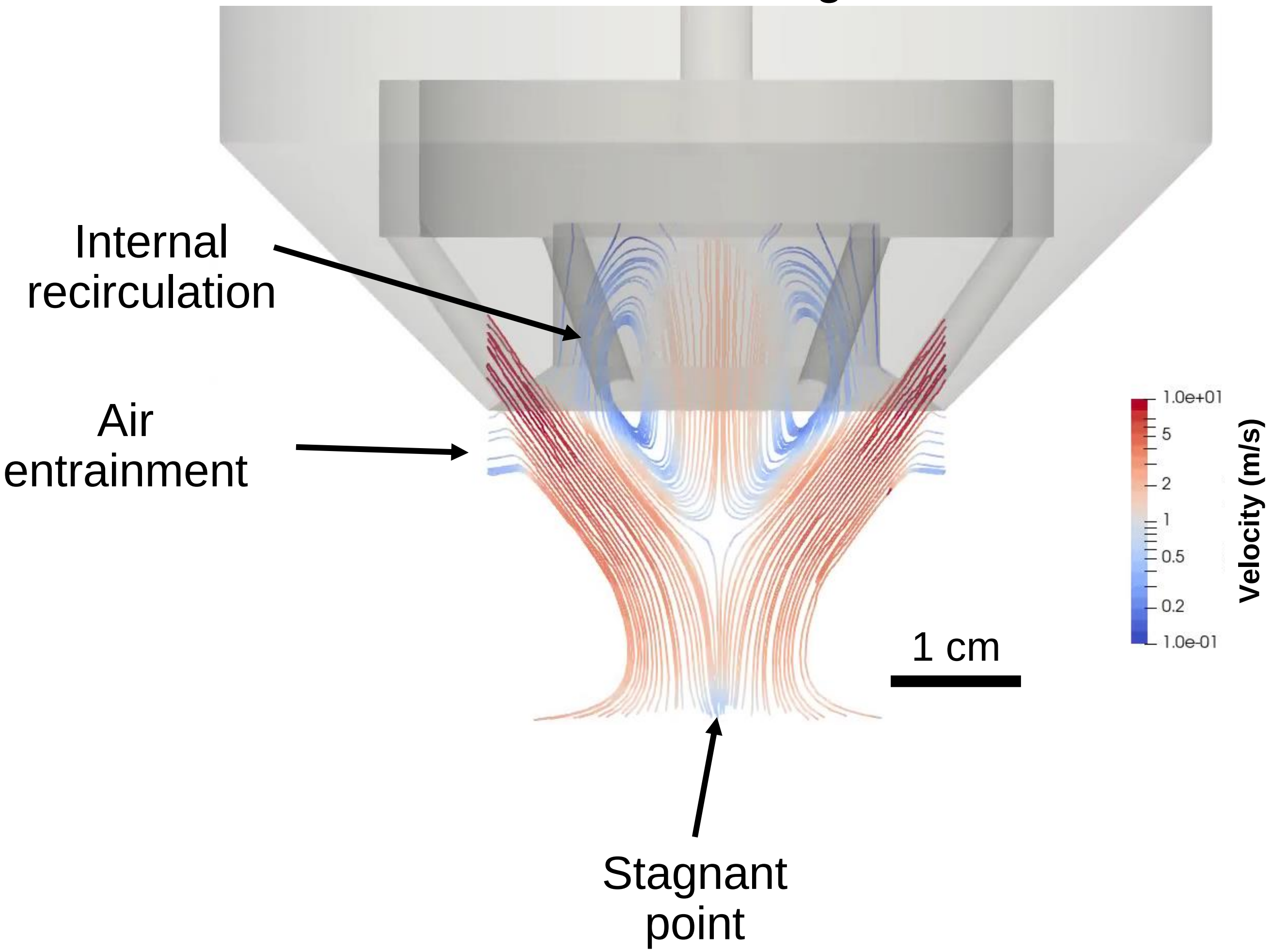
Each line connects quantities for a single combination of process conditions and outputs

Accomplishments: Utilizing Computational to Improve Gas Flow to Reduce Oxidation and Gas Porosity





CFD Simulation of Current Nozzle Design

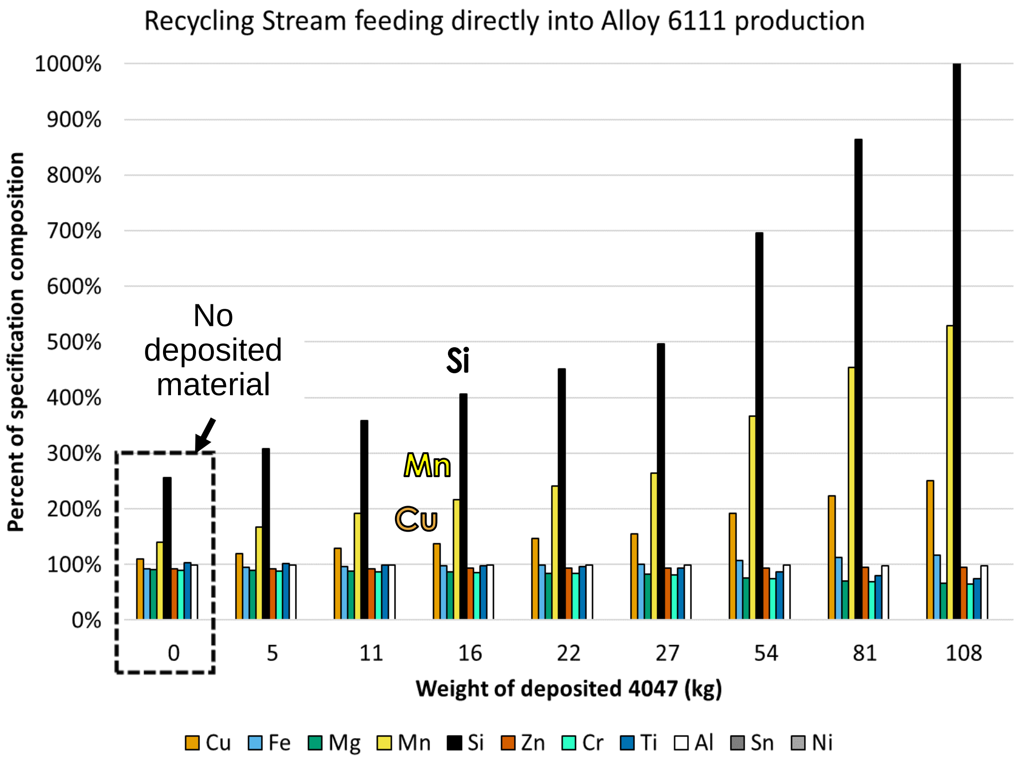


Accomplishments: Preliminary Recycling Analysis

- Example analysis for 4047 deposition on 6111 used for new 6111

- Can increase presence of Si in recycling stream, but **volume is expected to remain low** enough to mitigate challenges

- May offer a use for surplus recycled Si-rich scrap metal
  - Sustainable feedstock
  - AM may be an approach to increase utilization of this material stream, with effect of impurities mitigated through utilization of high cooling rates



FY22 Milestones

Milestone/Deliverable Name/Description	Criteria	Status
Deposition with different aluminum alloys: Print features on Al 6111 sheet with different aluminum alloys and characterize the heat accumulation in the 6111 sheet.	Demonstrate features >20 mm in largest direction. Deposit with at least three different alloys.	**Complete**
Quantifying the performance of deposited material: Characterize the mechanical properties of deposited materials for Q1 materials under laser hot-wire deposition conditions. Inform processing decisions for mitigating any observed issues with heat accumulation by using heat transfer modeling.	Show a deposited material with higher tensile strength than Al 4043 (>100 MPa).	**Complete**
Understand heat treatment response of modified Al 6111 sheet: Characterize the heat treatment response of at least one of the deposited precipitation hardened alloys and corresponding heat affected zone in the 6111 sheet.	Show the aging curve of the base alloy, interface, and deposited material through hardness measurements.	**On Track**
Demonstrate localized property improvement: Identify a preferred alloy to use for localized modification and demonstrate the improvement on local strength or stiffness on a 6111 coupon compared to the base coupon properties.	Demonstrate >25% improvement of the strength or stiffness of the unmodified coupon through local deposition of material.	**On Track**

Collaboration and Coordination

- Ford Motor Company
- Mazak
- Lincoln Electric
- CompuTherm
- Thrust 4 projects
  - Computational thermodynamics and kinetics
  - Atom probe tomography of graded alloy chemistries (PNNL)

Response to Previous Year Reviewers' Comments

- Not reviewed last year

Challenges and Barriers

- Deposition and Properties
  - Managing thermal conditions for thin sheets
  - Deposit quality as a result of process conditions and cover gas flow
- Complex shapes
  - Incorporate complex tool pathing
  - Utilizing hybrid processing by including machining
- Cost
  - Minimize cost through careful design and selective application of AM
  - Minimize cycle time through process optimization

Proposed Future Research

- Manufacturing and Materials Characterization
  - Heat affected zone characterization and heat treatment, CALPHAD, APT planned
  - Utilize computational tools to inform process improvements (e.g., nozzle design, parameter optimization)
- Demonstration
  - Sheet with stiffening features added with AM processing
  - Moving towards automotive scale demo (OEM interaction)
- Cost Reduction
  - Process optimization to minimize cycle time
  - Investigate use of surplus of “dirty” recycled stock, with excess Si and Fe

*Any proposed future work is subject to change based on funding levels

Summary Slide

Initial studies

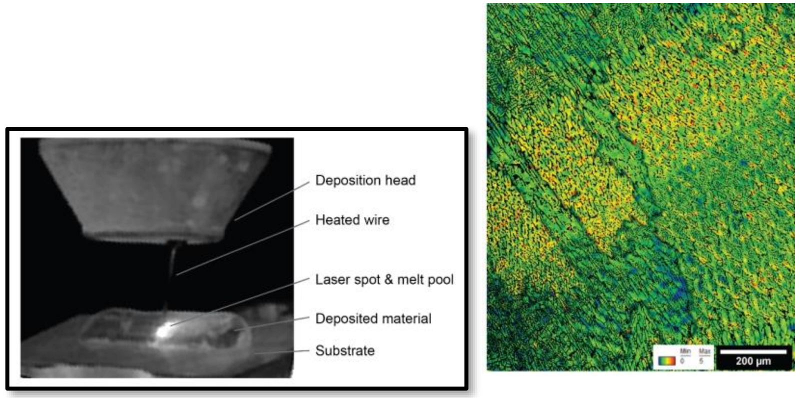
- Process development
- Microstructure characterization
- Property correlations

New System at ORNL

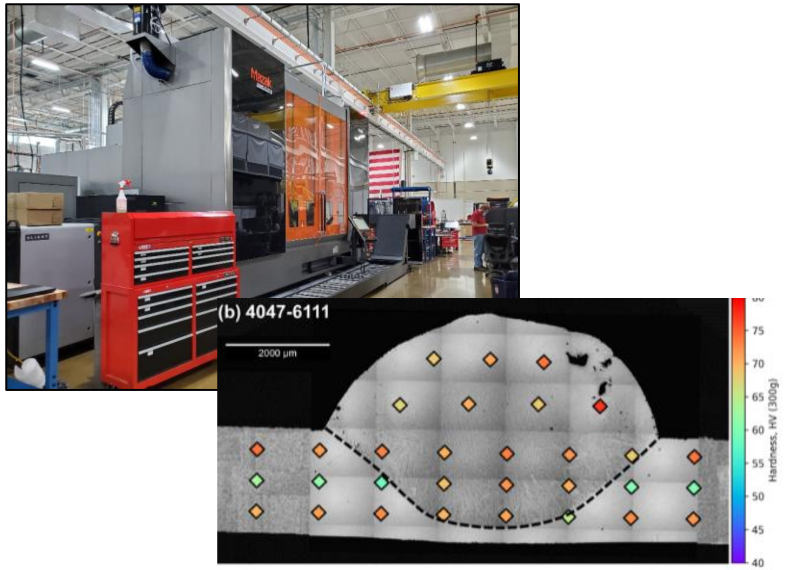
- System installation
- Deposition of multiple alloys
- Preliminary characterization

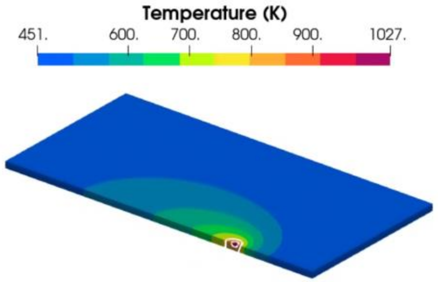
Computation

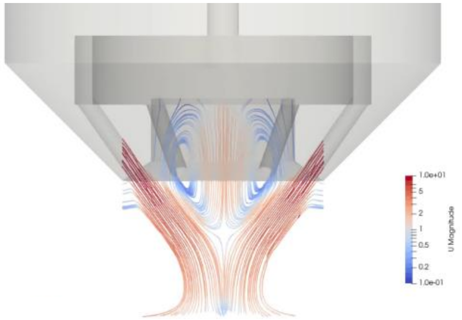
- Process modeling
- High dimensional data analysis
- Nozzle design



Localized deformation in melt pool boundary (right: kernel average misorientation)







Thank You

- Acknowledgements
  - ORNL: Maxim Gussev, Sarah Graham, Mithulan Paramanathan
  - Ford: George Luckey
  - Mazak: David Wilson, Paul Robinson, Dan Janka
  - Lincoln Electric: Chris Agosti